Available online at www.sciencedirect.com
SCIENCE DIRECT®
Renewable and Sustainable Energy Reviews
11 (2007) 116–132
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Biogas plants in Denmark: successes and setbacks

R.P.J.M. Raven[a,*], K.H. Gregersen[b]

[a]*Department of Technology, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*
[b]*Danish Research Institute of Food Economics, Rolighedsvej 25, DK 1958 Frederiksberg, Copenhagen, Denmark*

Received 22 November 2004; accepted 28 December 2004

Abstract

With 20 centralised plants and over 35 farmscale plants, the digestion of manure and organic waste is a well established technological practice in Denmark. These plants did not emerge without a struggle. Moreover, no new centralised plants have been established since 1998 and the development of farmscale plants has slowed down. This article reviews the experimental introduction of biogas plants in Denmark since the 1970s. We argue that three factors have been important for the current status of biogas plants in Denmark. First, the Danish government applied a bottom-up strategy and stimulated interaction and learning between various social groups. Second, a dedicated social network and a long-term stimulation enabled a continuous development of biogas plants without interruptions until the late 1990s. Third, specific Danish circumstances have been beneficial, including policies for decentralised CHP, the existence of district heating systems, the implementation of energy taxes in the late 1980s and the preference of Danish farmers to cooperate in small communities. The current setback in biogas plants is mainly caused by a shift in energy and environmental policies and limited availability of organic waste.

Keywords: Biogas; Denmark; Digestion

Contents

*Corresponding author. Tel.: +31 40 247 4413; fax: +31 40 244 4602.
E-mail addresses: r.p.j.m.raven@tm.tue.nl (R.P.J.M. Raven), khb@bio.sdu.dk (K.H. Gregersen).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2004.12.002

1. Introduction

Biogas is the name of the mix of CO_2 and the inflammable gas CH_4, which is produced by bacterial conversion of organic matter under anaerobic (oxygen-free) conditions. A biogas plant is a technical facility in which the biogas production process takes place. The sources for biogas production are principally a wide range of organic material. The completely stirred tank reactor (CSTR), which is the plant type applied in Denmark, is well suited for treatment of liquid animal manure and organic industrial wastes. The current use of biogas plants for manure and organic waste processing is relatively large in Denmark: in 2002, there were 20 centralised biogas plants (also known as community plants) and over 35 farmscale plants in operation, together producing about 2.6 PJ renewable energy and processing about 3% of all manure in Denmark. This is an achievement compared to other European countries [1,2].[1]

The Danish development of biogas plants has a long history. It is all but a linear development: both biogas plant concept and functionality of the plants varied over a period of more than 30 years and there were both successes and setbacks. This article reviews the 1973–2003 period and aims to provide new insights in three ways. First, the article gives a comprehensive historical description of biogas plant development in Denmark, focussing on different types (farmscale, centralised, co-digestion of household waste). Compared to (for example) wind turbines, only few articles address issues related to biogas plant development in Denmark and they mainly focus on centralised plants.[2] Second, the article aims to provide lessons from the Danish case and give insight in how a bottom-up approach stimulated a broad learning process and the formation of a rich social network. Finally, the article shows that the success of a research and development programme also depends on national circumstances like political choices, energy infrastructures and historically grown organisational structures, emphasising that technological development is partly subject to factors that cannot be (easily) influenced.

In the following sections, we present the Danish biogas case in three sub-periods. In Section 2, we describe early experiments with farmscale biogas plants in the late 1970s and early 1980s. In Section 3, we continue with the emergence of the centralised biogas plant between 1984 and 1998. Then, in Section 4, we describe a process of diversification: between 1996 and 2003, more centralised biogas plants were installed, but only until 1998. In the same period, there was a sudden rise in the implementation of farmscale biogas plants. Also new trajectories were explored including the separation and co-digestion of household waste in centralised biogas plants. We round up in Section 5 with conclusions and discussions.

[1] Data on energy production are from 2000 and apply to the biogas production from twenty centralised plants (2.5 PJ heat and electricity) and 25 farmscale plants (0.1 PJ heat and electricity). Data on the amount of manure are from 2000 and only apply the manure processed in the centralised plants.

[2] See for example [3].

2. Farmscale biogas plants

The development of farmscale biogas plants began in the 1970s. The 1973 energy crisis and high-energy prices stimulated farmers, research centres and technology companies to investigate energy generation from manure. One of the first farmers was Anders Lassen, who constructed a small plant, made of fibre glass, for about 400€. The first full-scale plant was constructed by Hans Aage Jespersen, in cooperation with a local blacksmith [4: 261]. These two plants were the first of many farmscale biogas plants in the 1970s and 1980s. The Danish grassroot movement (also known for their role in initiating the wind turbine development in Denmark) including Folke High Schools, local communities and farmers, constructed most of the plants. In an attempt to combine experiences, the Ministry of Trade established the Cooperation for Technological Development of Biogas Plants (STUB) in 1978.[3] An employee of the Danish Technological Institute chaired the group.[4] The group further existed of 10–12 engineers and agricultural specialists. The engineering firm Carls Bro A/S coordinated the activities, while the Danish Research Institute of Agricultural Economics was responsible for economic monitoring.[5] The group assisted in the construction of three plants, financed by the Ministry of Trade with a 3.6 million DKK grant (about half million Euros) [4: 263,5: 1].[6] Within the programme, three different types of plants were constructed in Gråsten, Gadebjerggård and Assendrup (e.g. batch versus continuous processing, gasfired boilers versus electricity production). Besides the three pilot plants, the group included four existing farmscale plants in the programme to record basic technical and economical information. A STUB service engineer visited the plants monthly to collect the information and report analysis results back to the farmers. The results were also published in a magazine called *Biogas Nyt* [5: 2–5].

Generally, the STUB programme demonstrated that biogas technology was by no means trouble-free. In 1981, an inventory among 21 registered biogas plants in Denmark showed that all plants had encountered severe technical problems. Five plants were completely out of operation without any plans for reinstatement. Three plants were not working, but the participants still sought for technical solutions. Four plants actually were in operation or in starting up phases, but problems prevented a stable operation.

Finally nine plants were more or less in stable operation [6]. The prospects were not promising. Most of the plants had been constructed for producing alternative energy, but biogas yields remained very much below the expectations (see Table 1). Most of the farmscale biogas plants constructed in the 1970s and early 1980s were abandoned in the following years and biogas plants seemed to become obsolete. However, a few actors (in particular, the Danish Folkecenter) continued to support farmscale plants (see Section 4).

[3] Samarbejdsgruppen for Teknologisk Udvikling af Biogasanlæg (STUB).

[4] Danish Technological Institute is a partly government financed research institute whose establishment dates back to 1906.

[5] Statens Jordbrugsøkonomiske Institut (SJI).

[6] In 1981, the programme was updated and the Ministry of Energy (established in 1979) financed the programme with another 3.2 million DKK. From the beginning, farmers criticised the STUB programme. Their main argument was that the STUB researchers did not want to learn from the existing plants. The biogas plant at the Højbogård Folke High School, for example, was shut out from measurements within the STUB programme because 'it was a well functioning plant with satisfying results'. This plant did not fit the aim of researching advanced biogas technologies.

Table 1
In 1981, STUB engineers calculated an average production of 140 m^3 biogas per 100 m^3 reactor tank

Location	Digester size (m^3)	Calculated production in 1981 (m^3/day)	Real production in 1982 (m^3/day)	Real production/calculated production (%)
Stenderup	45	63	45	71.4
Elsted	4 × 220	1232	17	1.3
Vilstrup	2 × 150	435	160	36.4
Sjoulundgård	6 × 60	504	180	35.7
Hjelmerup	100	140	80	57.1
Brested	100	140	85	60.7
Assendrup	2 × 200	560	150–200	26.3–35.7
Grasten	2 × 180	504	350	69.4
Gadebjergård	360	504	200	39.7
Lejre	20	28	6	21.4

In most cases, the real production was much lower. Data from [5:2,6:82].

The first period of Danish biogas plants demonstrates the messy and complicated character of developing new technologies. Increasing oil prices created expectations about alternative energy production. However, most of the actors involved had no or very limited experience with (manure) digestion. Users (farmers), for example, were not used to operate a biochemical plant. There were no specialised producers; biogas plants were often constructed by farmers in cooperation with local craftsmen. Moreover, there were many technical problems, often causing numerous downtimes. Technical optimisation did not result in a plant that could live up the expectations and farmers began to lose interest.

Drawing lessons from the failed projects, researchers suggested a move towards centralised biogas plants to overcome low biogas yields (and high production costs). This could also discharge individual farmers from a heavy workload. A Danish county in the North of Jutland took up the recommendations and implemented the 'Village Energy Project'.

3. Centralised biogas plants

In the early 1980s, the first ideas of larger (centralised) plants emerged. A centralised plant might benefit from improved technology and economies of scale, while it discharged individual farmers from the operation of the plant. The basic layout of the centralised plant concept is a centrally placed biogas plant, to which a number of farmers supply manure. In most cases, it is liquid manure, which is transported to the plant by trucks. In addition, organic waste from food processing industries is supplied. In some cases, source sorted household waste is also supplied. In the plant, the biomass mix is processed for 10–25 days. During this process the biogas is produced. It is converted in a combined heat and power production facility (CHP). Finally the now digested manure is transported to storage tanks at the farms or near the fields where in the end it is used as a fertiliser (Fig. 1).

In the mid 1980s, several Danish villages decided to establish centralised biogas plants. The North Jutland County Council implemented the 'Village Energy Project' [7]. This project initially included the construction of four biogas plants throughout North Jutland (although only two have been constructed), the first in 1984 in Vester Hjermitslev. The

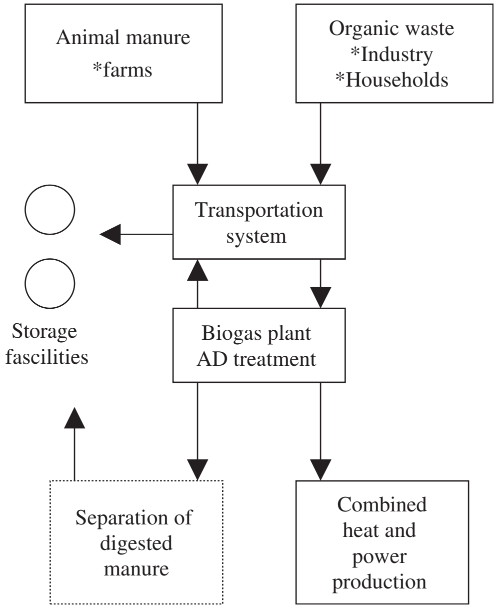

Fig. 1. The centralised biogas plant concept.

objective was to demonstrate the self-sustainability of the town regarding energy; unemployment issues were also important [7,8]. The independent institution *Vester Hjermitslev Energiselskab* owned the plant. Its board of directors consisted of four members appointed by local inhabitants and three by the directors of *Vester Hjermislev Heating*, the local district heating company. The North Jutland County Council lent 8.4 million DKK (about 1.2 million Euros) and the national government granted the remaining four million (over half million Euros).[7] The Bigadan company, also involved in the construction of some of the farmscale plants in the 1970s, supplied and constructed the plant.

As the first centralised biogas plant in Denmark, the Vester Hjermitslev plant was originally based only on manure, solid and liquid. It was equipped with a pre-sanitation facility. It had a high-pressure gas transmission and storage system, two engines for heat and power production, and a large heat pump, which was used in periods when heat consumption was high. Especially the gas system and the heat pump and the pre-sanitation equipment caused numerous operational problems in the first years of operation. Consequently, the plant was reconstructed in 1988–1989, which improved plant operation dramatically, and enabled the plant to process organic industrial waste, which improved energy production significantly.

In 1985, the local independent institution *Vegger Energiselskab* in Vegger commissioned the construction of the second centralised biogas plant. The design of the plant, the second one in the ‘Village Energy Project’, was similar to the first plant, except that it operated at a different temperature (55 °C instead of 35 °C). An extra pasteurisation step could therefore

[7]The total costs of 12.4 million DKK (1.7 million Euro) also included the costs for a wind turbine as well as a slurry storage tank.

be left out. The third centralised biogas plant was constructed in Skovsgård by the Bigadan company in 1986. The original layout (the plant was reconstructed in 1990) was similar to the layout of the Vester Hjermistlev plant (also supplied by Bigadan). The plant processed 40 tons of manure and an additional 15 tons of industrial organic waste per day [7]. Finally, another plant was constructed in Davinde in 1987. Although operation of these plants improved compared to the farmscale plants, performance in terms of biogas production was still limited. As a result, the North Jutland county withdrew as supporter of biogas technology [3]. The social network threatened to fall apart, reducing the viability of manure digestion in Denmark.

However, the national circumstances in the energy and agricultural domain changed after 1985. First, the global oil prices decreased enormously, making fossil fuels an inexpensive fuel again. In the years before 1985, however, the Danish government, the two Danish energy companies ELSAM and ELKRAFT (now Energi E2), and social groups representing the grassroot movement (Folke High Schools, several scientists, energy offices) had participated in lively discussions about alternatives for fossil fuels. By the mid 1980s, nuclear power was rejected as an option in favour of an increased exploration of domestic fossil fuels (in particular, natural gas) and alternative sources like wind power and biomass. Moreover, efforts to improve energy efficiency and energy savings had been successful and large new power plants were no longer a necessity [9:1120]. The construction of a new natural gas network was also part of the new energy policy framework. The government (who had gained a decisive voice in the energy sector by that time) decided to stimulate the construction of decentralised heat and power plant. District heating was an established infrastructure in Denmark, but most plants only produced heat and no power. The idea was to convert the heat boilers into CHP plants. The government favoured, in particular, natural gas (because it created a market for the newly constructed natural gas infrastructure). In locations where there was no natural gas available (about a quarter of Denmark), biomass should be used instead. One of the options was centralised biogas plants. To prevent the reintroduction of oil, the Danish government decided to raise taxes on energy carriers.[8] The new tax system resulted in high taxes on oil products, lower taxes on coal, and relatively high taxes on electricity. Renewable energy and natural gas were both tax-exempted [10: 30]. This resulted in about the same electricity price for households before and after the oil prices decreased [11]. Energy from biogas was now at least more competitive than in many other European countries after the decrease in global oil prices.

Second, there were several changes in the agro-environmental framework in Denmark (like in the rest of Europe). Before 1984, agriculture was not considered to be an environmental problem in Denmark. In 1984, the Danish Environmental Protection Agency (EPA) published a report on the pollution caused by nitrates leaching from agricultural land [12]. The debate triggered by this report resulted in a number of agro-environmental regulations, including an obligation for farmers to have sufficient storage capacity for manure for 6–9 months. This forced farmers to spread manure only when the risk of nitrate leaching was low and store it for the rest of the year. In 1987, the EPA published the Water Environment Action Plan I, which included a major reduction goal for the leaching of nitrate in agriculture. This plan regulated the number of animals per hectare as well as the maximum input of nitrogen per hectare. In several Danish regions,

[8]Energy tax on oil and electricity was introduced in 1977 and on coal in 1982 [10: 30].

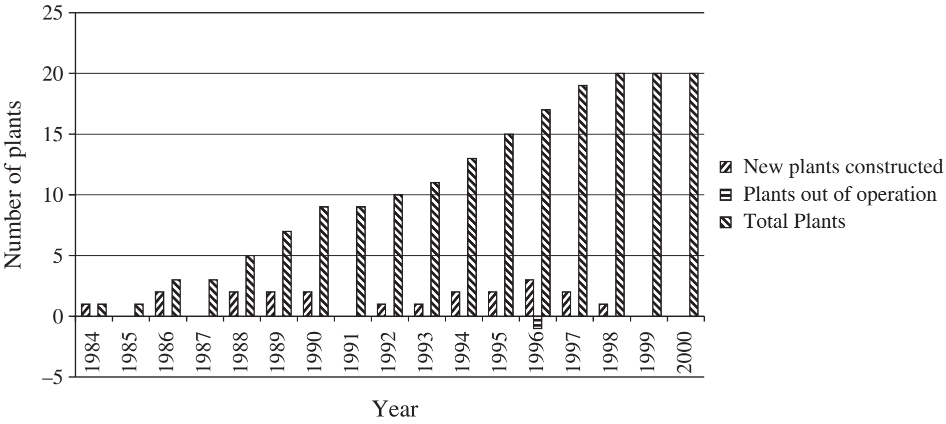

Fig. 2. Increase of the number of biogas plants in the period 1984–2000. Data from [8].

farmers were now facing a manure surplus and required a distribution method [13].[9] This stimulated farmers to participate in centralised biogas plant organisations, because these organisations could take care of the transportation and distribution of manure.

The Danish Energy Agency (DEA, an agency of the Ministry of Energy), the EPA and the Ministry of Agriculture decided to exploit these developments to establish a framework for the further investigation of centralised biogas plants.[10] In 1988, they started the Biogas Action Programme. This programme focussed on the construction and monitoring of biogas plants, information activities and research and development work.[11] Also included was an investment grant for centralised biogas plants up to 40% and a financing scheme with long term, low interests indexed loans. The programme was to be executed between 1988 and 1991 and included the construction of five new biogas plants. Also the four previous constructed plants were observed in the monitoring programme. After 1991, the ministries continued the programme several times until it was stopped in 2002 [7: 4,16: 9].

[9] Later, in 1992, the Ministry of Agriculture, Foods and Fisheries implemented a plan for 'sustainable agriculture' in which also the European legislation was implemented, including an obligation for farmers to do fertilizer bookkeeping.

[10] The Danish Energy Agency became the Danish Energy Authority in 2002. For reasons of clarity, I will stick to the term Agency throughout the article.

[11] The program build upon the earlier experiences with centralised biogas plants in Vester Hjermitslev and Vegger. Although these plants had seen severe technical problems, lobbying by the 'Committee for Renewable Energy' (Teknologirådets Styregruppe for Vedvarende Energi) had created a more positive perception about centralised biogas plants among the Danish ministries. In this committee, scientists and small and medium manufacturers of biogas plants, wind turbines and solar technologies participated. The committee, with Niels Meyer as chairman, was formed in 1981 and the focus was on stimulating the development of new industries, in particular, industries for renewable technologies. It had a mandate to support projects financially with state funds. This committee took a pragmatic approach, focussing on practical solutions for problems as they occurred (as opposite to more scientific approaches often taken in other countries, e.g. as in the case of wind turbines in California, USA). The committee existed until 1991. Besides incidental support to the first centralised biogas plants, the committee financed several of the experiments with farmscale plants conducted by the Folkecenter (see Section 4) [14,15].

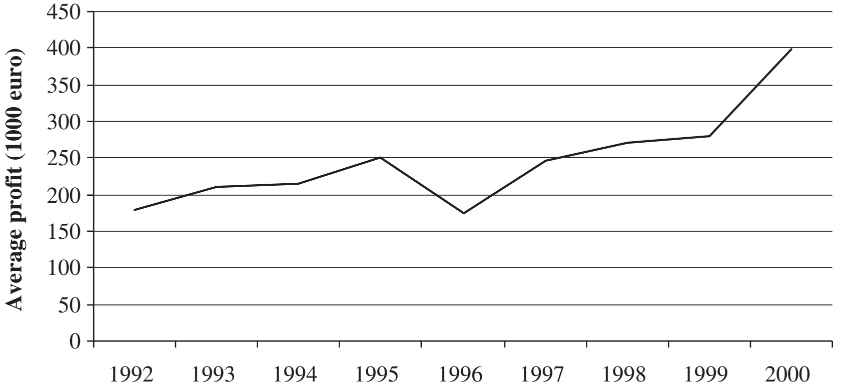

Fig. 3. Average profit of centralised biogas plants. Average profit is the total profit of all plants, divided by the number of plants. Profit per plant is calculated as the income (heat, electricity, gate fees) minus operating costs (maintenance, cost of labour, etc.). Operating costs do not include the pay-off of loans [17].

Within the framework of the Biogas Action Programme, one or two centralised biogas plants were constructed annually (see Fig. 2). Over the years, the plants improved gradually, the biogas yields increased and the economic feasibility improved throughout the 1990s (see Fig. 3). Three issues have been important for the successful development of biogas plants in these years. First, the Danish authorities applied a bottom-up approach as much as possible and stimulated interaction between farmers, researchers, biogas plant companies (suppliers), biogas plant operators and public authorities. This contributed to the establishment of a broad social network involved in biogas plant development and stimulated exchange of experiences between biogas plants and between social-groups. As a result, innovations were easily transferred between biogas plants. A gas cleaning system (based on adding a little air), for example, discovered at a plant in Fangel in 1993, quickly diffused among new plants, while some of the older plants also started using the technique [16: 10]. The bottom-up approach also stimulated a broad learning process. In particular, the interaction of farmers, researchers and biogas plant operators was important. Agricultural benefits like centralised storage capacity (lower investment costs and reduction of transport miles for the individual farmer), the reduction of artificial fertilizer use (the digestion process improves the fertilizer characteristics of manure and biogas plants provided farmers with detailed information of the composition of the manure), and the improvement of veterinary aspect (digestion kills of pathogens and weeds) emerged as important incentives for continuing participation.

Second, all biogas plants combined the digestion of manure with the digestion of organic waste. In particular, fatty waste and fishery waste were used. In most plants, organic waste was added up to 20%, which improved biogas yields (and thus energy sales) enormously. Moreover, the biogas plants received a gate fee for processing the waste, which improved the economic feasibility further. Co-digestion also fitted the interests of the three participating ministries: increasing the production of renewable energy was important to the DEA, organic waste recycling for the EPA and supervision on waste and manure

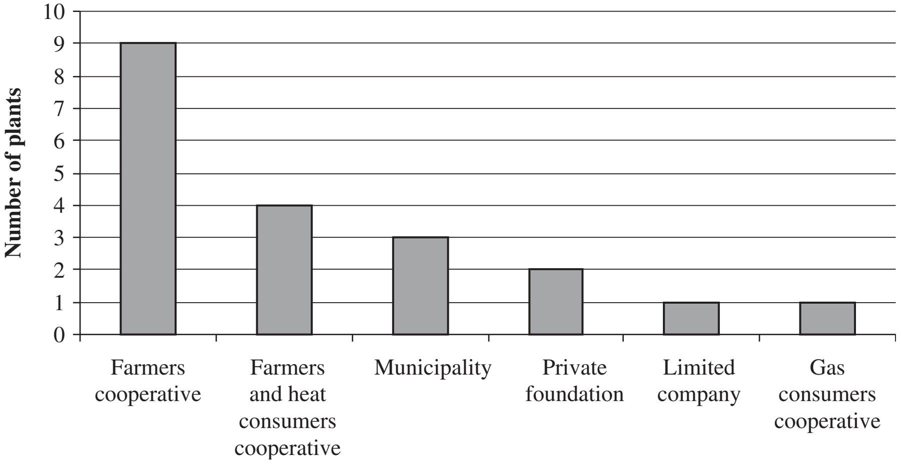

Fig. 4. Different types of ownership in Danish centralised biogas plants. Data from [7,8].

streams and veterinary aspects for the Ministry of Agriculture. In contrast with, for example, the Dutch case, all three ministries supported co-digestion.[12]

Third, a key element in the development of centralised biogas plants is the cooperation between farmers in groups of 5–100 farmers.[13] The cooperative organisation emerged as the dominant organisational structure for biogas plant after 1987 (Fig. 4). These cooperatives carried out the transportation and distribution for the farmers. Some cooperatives also constructed local storages near the fields of the farmers and rented these to the farmers. This relieved the farmers from large investments for private own storage space. The cooperatives were not established for making profits. They were financed with loans and granted by the government. Moreover, they had an income from energy sales as well as from gate fees for receiving industrial waste. This enabled farmers to process their manure without paying, while in all other European countries farmers had to pay a processing fee [20: 167].

In sum, this section showed that contextual changes in the late 1980s created opportunities for centralised biogas plants. The Danes were able to exploit the opportunities through a good innovation process, creating internal momentum. By the mid-1990s, the niche of centralised biogas plants was ready for wider take-off. But this

[12]Co-digestion was until recently legally impossible in the Netherlands. The major manure surplus in the Netherlands did not encourage adding extra waste to the manure. In particular, the Dutch Ministry of Agriculture hesitated to allow co-digestion [18].

[13]The cooperative also fitted a general preference among farmers in Denmark. The cooperative is a well known structure in Danish society, for example, for buying fertilisers. A cooperative has no private capital, the members own the association and not a private institution (e.g. a company with private capital). With a lack of special cooperative legislation, Danish farmers were quite free to frame their association rules as they wished. This enabled them to establish cooperatives completely for the benefit of its members. In the case of artificial fertilizers, for example, the cooperative structure enabled farmers to set out much stronger demands on prices and quality than in other European countries. This has contributed to a relatively strong position for farmers in Denmark. The cooperation between farmers for setting up a biogas plants (and in some cases for supplying manure to a plant) was thus a logical step in the development of centralised biogas plants [19].

development was frustrated by major contextual changes, which created new barriers and uncertainties.

4. New setbacks and diversification

The last centralised biogas plant was constructed in 1998, despite major improvements in technological and economic performance. The main reason was the ongoing liberalisation of the energy sector. In May 1996, the government passed an amendment to the Danish Electricity Supply Act to permit private companies and distribution companies of sufficient size to buy power from third parties [11: 9].[14] In 1999, the parliament confirmed a new energy act, the Danish Energy Reform. The reform aimed at a complete transformation of the Danish energy sector after 2003, including the way renewable energy was stimulated.[15] The transition created uncertainty for Danish renewable energy projects. In the case of biogas plants, the Danish Energy Agency sent a "Bill to Amend the Act on Subsidies for Electricity Production" to a large number of actors for hearing, including the Association for Biogas, The Danish Farmers Union and the Biogas Group [22]. The Bill proposed a new model for stimulating renewable energy. Traditionally, the price paid per kilowatt hour for electricity from biogas was between €0.06 and 0.075. The bill would replace this fixed price scheme with an uncertain price, in particular, on the longer term, when both the conventional electricity price and the price for 'green certificates' could fluctuate. The Biogas Association negotiated for a long time with the Agency, in particular, about specific transition rules that would at least guarantee the prices until the green certificate market would be fully operational (not until 2005). The uncertainty created by the new scheme halted the investment in new plants after 1998 [23].

Also other developments are part of the explanation why no new centralised plants were constructed. First, the centralised biogas plant had become very much dependent on organic waste for feasible economic operation. Obtaining the organic waste became increasingly difficult, because more biogas plants started using the waste. Second, the Danish people elected a new government in November 2001. The government, a liberal/conservative coalition, resulted in a shift in environmental and energy policies in Denmark. Generally, this government had less focus on environmental issues in energy generation and more on cost efficient energy supply. Many grants, funds and R&D support schemes were cancelled (see Table 2). Moreover, the policy shift increased the level of uncertainty (already created by the liberalisation process) and investors and companies waited for new policy documents. The direct consequence for biogas plants was that the Biogas Action Programme was stopped in 2002 [25: 4,26].

[14] The amendment was originally planned to become fully implemented from 1998. However, uncertainties rising from possible take-overs by foreign companies resulted in a postponement to 2001 [11: 12,19: 600].

[15] Previously, the government had used a feed-in model. In a feed-in model, a long-term fixed price is guaranteed for electricity obtained from renewable sources. This results in a relatively high level of certainty about payback rates on investments. Investors are relatively easily able to obtain financing. Inspired by expectations about a new model becoming the standard in Europe, The Danish government decided, as part of the energy reform in 1999, to replace the feed-in model with a new model, i.e. a certificates trading model. In such a model, producers of renewable energy receive a total payment consisting of the market price of conventional electricity supplemented by the market price of a green certificate. Consumers are then obliged to buy a specific amount of green certificate, which creates a market for these certificates, and thus for renewable energy [21,24].

Table 2
Programme reductions in Denmark after new government

Programme	Previous government support (million Euro)	New government support (million Euro)
Development and information of renewable energy	20	0
Energy research	14	5
Utilities energy research	10	10
Energy savings and fuels switch in industry	19	0
Investment grants for biomass CHP	4	0
Joint Implementation and Clean Development Mechanism	0	17

Join Implementation and Clean Development Mechanisms are perceived as instruments more compatible in a liberalised energy market [26].

To summarise, the exploitation of favourable circumstances in the late 1980s were important in initiating the Biogas Action Programme, and the Danish way of developing the centralised biogas plant concept was crucial for the success of the programme. However, uncertainty about energy policies, less availability of organic waste and the shift in energy and environmental policies from 2002 stopped further development after 1998, despite increased performance. Nevertheless, the development of Danish biogas plants branched into new directions.

Two new biogas plant concepts emerged. First, several municipalities started experiments with the separation of household waste. The municipalities tried to anticipate a national obligation for the separation of household waste (which has never been implemented in Denmark). Another reason was a taxation system for waste, implemented in 1987. During the 1990s, taxes on landfill and incineration were increased several times from 40 DKK/ton in 1987 for both landfill and incineration to 260 DKK/ton for incineration and 335 DKK/ton for landfill. Additionally, the Danish government implemented a ban on the landfill of combustible waste in 1997. As a result, municipalities were increasingly searching for new waste processing methods. Some of them approached an existing biogas plant or commissioned a new one. The Herning municipality took a leading position. In 1993, the municipality implemented source separation of waste in some parts of the town. The organic waste was collected in plastic bags, which needed to be removed before adding the waste to a biogas plant. Therefore, the municipality constructed a small-scale pilot plant for the treatment of the waste. In 1994, they commissioned a full-scale plant at the Sinding biogas plant and another one in Studsgaard in 1996. In Studsgaard, a pasteurisation tank destroyed pathogenic bacteria and infectious germs in a pre-sanitation tank. The waste was then mixed with liquid manure and digested at a temperature of 55 °C for a period of 16 days. A separation process after digestion finalised the first process line. Another line processed manure together with organic industrial waste [27–29].

Also the municipalities of Århus; Aalborg (near Vaarst and Fjellerad) and Nysted experimented with the co-digestion of organic household waste. All these plants suffered from an unsatisfactory system for the separation of plastic bags. Plastic bags were not affected by the digestion process and if they are not separated from the waste, then they

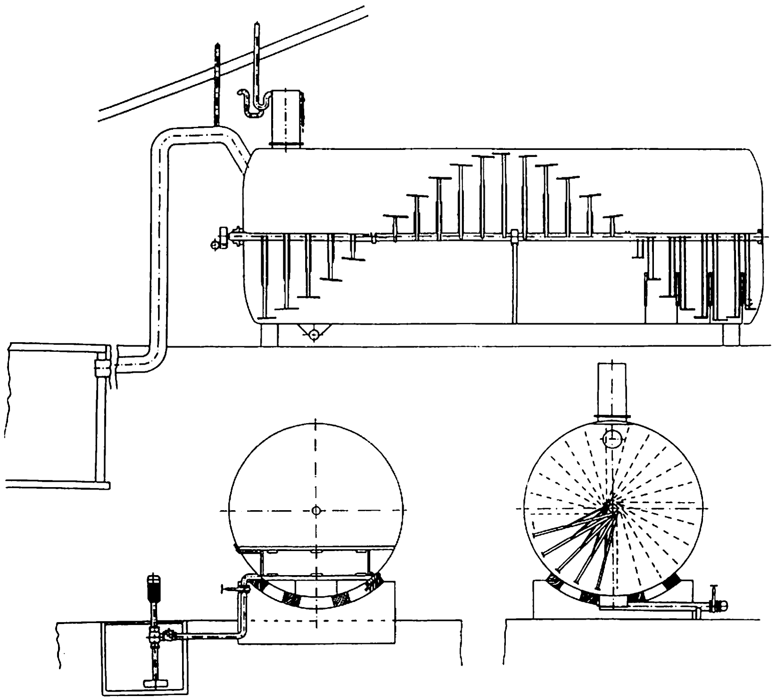

Fig. 5. The layout of the Smedemeister plant [34]. The top picture shows the digester from the side, the other picture shows the same digester, but from the back and the front. In the top picture, manure is added from the left. Inside the digester is a horizontal steering mechanisms, which transports the manure from left to right.

end up on the farming land. This would make the biomass unsuitable for fertilizing purposes [30: 41].

The second development was the reintroduction of farmscale biogas plants in Denmark. In particular, two types of farmscale plants were implemented. The first type was called the *Smedemester* (Blacksmith) biogas plant. Employees of the Folkecenter for Renewable Energy (including Preben Maegaard and Niels Ansø) had continued working on improving the farmscale biogas concept in the early 1990s. Through local testing and experimenting as well as contacts with the German biogas industry, the Folkecenter was able to develop two standardised Blacksmith plants.[16] The first plant was a horizontal steel tank, manufactured in industrial workshops of a size between 50 and 300 m^3 (see Fig. 5). The manure was added on one side of the digester and a horizontal stirrer transported the manure slowly in about 15–25 days to the other side of the tank. The second Blacksmith plant type was a vertical tank built on-site in sizes from 400 m^3 and upwards. The biogas was used as a power source in traditional combined heat and power units. Later these were displaced with dual-fuel engines. Dual-fuel engines use 5–15% diesel mixed with the biogas. The advantage of the engine is that its power production efficiency is higher, and therefore economically more attractive for smaller biogas plants. In addition, it performs

[16]The ‘Committee for Renewable Energy’ played an important role in the continuous development of farmscale biogas plants. They financed several of the experiments conducted by the Folkecenter [14].

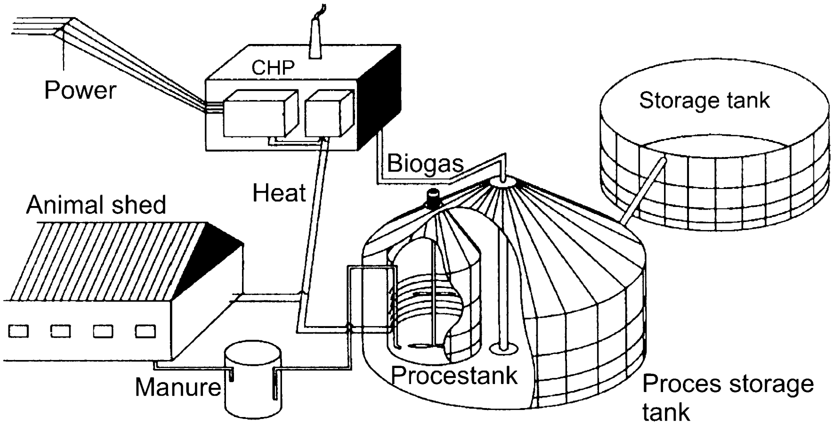

Fig. 6. Layout of the soft Cover digester type [36: 31]. Manure is added from the animal shed into the procestank. Digested manure overflows into the process storage tank. Extra storage is provided by an external storage tank. Biogas produced in the digestion process is transported to a combined heat and power unit (CHP) for the production of power (fed back into the grid) and heat (used for maintaining the digester temperature and heating the animal shed).

better in starting up the combustion process. In order to optimize the biogas yields, the Folkecenter also developed a computing programme for controlling the process [31–35].

A second type of farmscale biogas plant was developed by the Bigadan company during the 1970s and 1980s and consisted of low concrete digesters. This digester type was also supplied to the first centralized plant in V. Hermitslev. Another concept, the Soft Top Plant Concept, had a membrane fastened to a floating ring at the edge of a traditional slurry storage tank. The membrane was inflated by the emerging biogas. Throughout the 1990s, several concepts were developed, which were based on conventional slurry storage tanks covered with membranes. One of these, the Soft Cover Plant, had a small concrete digester inside a storage tank. When the digester was full, the manure could overflow into the storage tank (see Fig. 6). A membrane sealed on the storage tanker (either soft or hard) collected the biogas [33,35].

These designs were at the basis for the development of farmscale plants in Denmark in the early 1990s. Initially the number of plants implemented increased slowly. However, in the mid 1990s the number of plants began increasing (see Fig. 7). Although important, technological improvements only partly account for the increase. Two other issues strongly pushed the diffusion of the farmscale biogas plant.

First, the average size of Danish farms had increased: 20% of Denmark's pig farms produced 56% of all pigs in 1970, compared with 75% of all pigs in 1997 [38: 12]. Some of the larger farmscale biogas plants could now be as large as a centralised biogas plant.

These structural changes in agriculture improved the economics of scale of biogas plants on farms.

Second, a change in the attitude of the Danish government in the mid-1990s resulted in increasing support for farmscale plants. In 1994, the DEA established a working group for monitoring the performance of farmscale plants to increase insight in their financial and technical performance. The establishment of this working group occurred against the

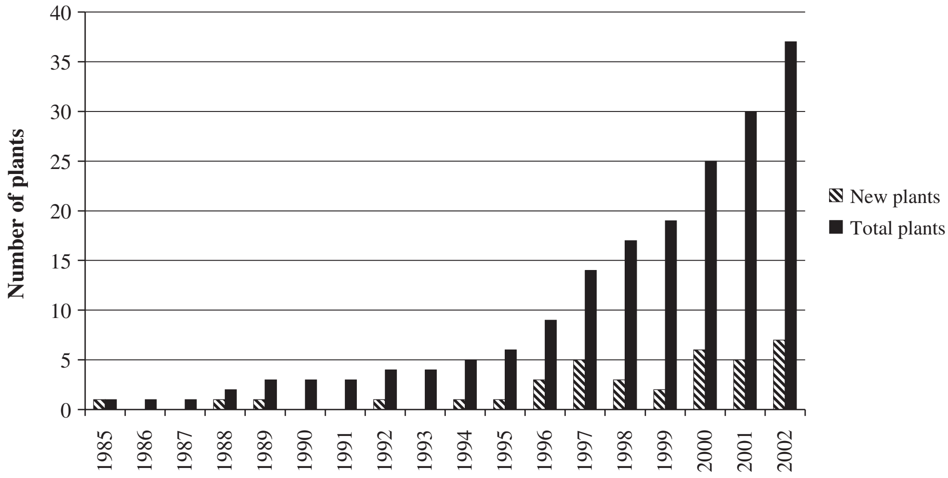

Fig. 7. Increase in the number of farmscale plants in Denmark [36,37].

backdrop of an increasing interest to reduce greenhouse gas emissions in agriculture. The 1997 Kyoto protocol emphasised the role of gasses like methane next to CO_2.

The agricultural sector was the main producer of this gas (from manure). In 1998, the Danish government implemented the second Action Plan on the Aquatic Environment, which tightened several standards for emissions from agriculture. Subsequently, the government made grants available for the agricultural sector for investments in farmscale plants. They expected on the basis of the monitoring programme that the performance of farmscale plants had increased sufficiently, but that breakthrough was prevented because of high investment costs [39]. The support included investment grants up to 40%, comparable to the level of grants in the early 1980s for centralised biogas plants. This proved to be the final push for a rapid diffusion of farmscale plants in Denmark. Nevertheless, the investment grant was only in place for a limited period and the number of farmscale plants did not increase much further after 2002. The future for farmscale plants is uncertain.

5. Conclusions and discussions

The development of biogas plants in Denmark is generally recognised as a success. Over 30 years of research, experimenting and, plant construction and improvement have resulted in a situation with one of the highest number of biogas plants in Europe. Denmark is, in particular, known for its centralised biogas plant concept: a community of farmers cooperating in an organisation to supply and digest the manure in a centrally located biogas plant. There are many advantages to a centralised biogas plant: it generates renewable energy, it enables the recycling of organic waste, it can play a role in manure distribution and storage and improve the veterinary aspects of manure, it can reduce fertilizer use, and it contributes to the reduction of the greenhouse gas methane. These advantages make a biogas plant a technology that is able to combine several environmental benefits across different sectors. The fact that the Danes recognised biogas

plants as a multi-functional technology is the crucial success factor for biogas plant in Denmark.

Biogas plants, however, have not always been recognised as an integrated, environmental sound technology. In the 1970s and 1980s, alternative energy generation was the dominant driver for implementing biogas plants, in particular, on a farm level. Other advantages were only hardly recognised at that time. Because plant operation was unstable, biogas yields were low and farms were too small for reaching economic feasibility, farmers had no reason to continue operation. Several villages, however, saw prospect for a centralised plant, which could overcome some of the difficulties from farmscale plants. Still, energy generation was the dominant incentive.

The perception of a centralised biogas plant as an all-round environmental technology emerged under the Biogas Action Programme. Although many stimulation programmes for renewable energy are implemented in various countries in Europe, we believe that three key-issues made the Biogas Action Programme a success. First, the participating ministries applied a bottom-up strategy and stimulated interaction between various social groups. This contributed to the establishment of broad social social-network that supported the development of the centralised biogas plant and focused on interactive learning. Many of the advantages that are now recognised emerged from this bottom-up approach through the participation of many actors (e.g. centralised storage, reduction of artificial fertilizer use, reduction of transport miles). A similar approach is observed in the case of Danish wind turbines [40]. Second, continuity of the action programme and financial support for a long period has also been important. Most renewable energy technologies require long development periods and dedicated actors are important for building up experiences and competencies. If development programmes are interrupted, then individuals and companies might go working in different areas and experiences may be lost. We have observed this for biogas plants in the Netherlands elsewhere [41]. Third, specific Danish circumstances have been very fruitful for the development of the centralised biogas plant concept. The Danish policy for establishing decentralised CHP on natural gas and biomass, the existence of many district heating systems, the implementation of energy taxes in the late 1980s and the preference of Danish farmers to cooperate in small communities have all favoured the development of the centralised biogas plant concept.

The fact that an increasing number of advantages was recognised stimulated ministries, farmers, researchers and biogas plant suppliers to continue improving the centralised biogas plant. Plant improvement enabled a process of diversification after the mid 1990s, but also wides, non-technical developments were important. Pushed by waste policies, municipalities saw new opportunities for processing organic waste. Also the farmscale biogas plant was reintroduced. Many farmscale plants were implemented, in particular, due to a temporary investment grant and an increase in the average farm size. Also the role of the Folkecenter is crucial. They continued to work on improving farmscale biogas plants. This illustrates that successful diffusion of technologies depends on dynamics on multiple levels, i.e. local experimenting and technological innovation versus wider, contextual factors.

Recent developments in Denmark have effected the implementation of biogas plants. Uncertainty about subsidy schemes and energy policies from a new government have stopped all investments in centralised biogas plants and the Biogas Action Programme has ended. The present circumstances are much less favourable than they were in the late 1980s and early 1990s. Stimulation of biogas plants (and renewable energy sources in general)

has to occur under free market conditions. A similar long-term stimulation and learning programme as the Biogas Action Programme will probably not return in Denmark for farmscale biogas plants or for co-digestion of organic household waste. This complicates the further exploration of these technologies. Several advantages, discovered in the framework of the action programme and contributed to the success of centralised biogas plants, do not necessarily apply to these plants (e.g. centralised storage). Also for centralised biogas plants, the future is uncertain. Although the development of this type of biogas plant has advanced the most in Denmark, a long period without the construction of new plants or further research will result in a loss of experiences from the past.

We can draw important lessons from this case study that can be useful for policy makers or other advocators of sustainable technologies. The introduction of sustainable technologies is often a very long-term and fragile process. New technologies often need to be nurtured for over decades, before sufficient socio-technical momentum emerges. Both technological performance as well as social support fluctuate and might only stabilise after decades of development. Single actors are often not capable of providing support for such a long process. It requires an approach that stimulates distributed support from various actors. Social network building including industries, researchers, users and policy makers is an essential ingredient for successful technology introduction, in particular, in the case of sustainable technologies. Moreover, such an approach should focus on learning not only about technological improvements and economic performance, but also about regulatory frameworks, the user context and other parts of the selection environment. Alignment between the technical, economic, regulatory and social context can provide the basis for building up momentum, until the technology is able to survive on its own.

Acknowledgements

This research has been made possible with a grant from the Netherlands Organisation for Scientific Research.

References

[1] Holm-Nielsen JB, Seadi TA. State of the art of biogas in Europe. In: Proceedings for the Nordic and European bioenergy conference bioenergy 2001, 15–28 September 2001, Aarhus 2001.
[2] Andreasen A. Status and perspectives for an accelerated development of biogas. In: Proceedings for the Nordic and European bioenergy conference bioenergy 2001, 15–28 September 2001, Aarhus 2001.
[3] Maeng H, Lund H, Hvelplund F. Biogas plants in Denmark: technological and economic developments. Appl Energy 1999;64:195–206.
[4] Beuse E, Boldt J, Maegaard P, Meyer N, Windeleff J, Østergaard I. Vedvarende energi i Danmark: en krønike om 25 opvækstår 1975–2000.: Organisationen for Vedvarende Energi; 2000.
[5] Groen G. Biogas technology in Denmark—comparison of anaerobic digester designs.: Carl Bro International; 1981.
[6] Operations Analysis Centre. Biomass and regions: regional case study Denmark.: Commission of the European Communities; 1982.
[7] Danish Energy Agency. Update on centralized biogas plants. Copenhagen: Danish Energy Agency; 1992.
[8] Seadi TA. Danish Centralised Biogas Plants—plant descriptions. Esbjerg: Bioenergy Department, University of Southern Denmark; 2000.
[9] Hadjilambrinos C. Understanding technology choice in electricity industries. A comparative study of France and Denmark. Energy Policy 2000;28:1111–26.
[10] Ministry of Energy. Energy 2000. Copenhagen: Ministry of Energy; 1990.
[11] IEA. Energy Policies of IEA countries—Denmark: 1998 review. Paris: IEA; 1998.

[12] Miljøstyrelsen. NPO-Redegørelsen. Copenhagen: Miljøstyrelsen; 1984.
[13] Mogens M. Environmental administration in Denmark. Copenhagen: Ministry of Environment and Energy; 1995.
[14] Maegaard P. Personal communication (10.09.04). Folkecenter for Renewable Energy; 2004.
[15] Illum K. Personal communication (31.01.05). Eco-Consult; 2005.
[16] Danish Energy Agency. Progress report on the economy of centralized biogas plants. Copenhagen: Danish Energy Agency; 1995.
[17] Danish Institute of Fishery Economics. Centralised biogas plants—integrated energy production, waste treatment and nutrient redistribution facilities. Copenhagen: Danish Institute of Fishery Economics; 1999.
[18] Raven RPJM, Verbong GPJ. Dung, sludge and landfill. Technology and Culture 2004;45:519–39.
[19] Pedersen C. The Danish Co-operative Movement. Danish information handbooks 1977.
[20] Danish Energy Agency and Krüger Bigadan. Centralised digestion of animal manure.: European Commission; 1992.
[21] Meyer NI, Koefoed AL. Danish Energy Reform: policy implications for renewables. Energy Policy 2003;31:597–607.
[22] Folketinget. Bill to amend the act on subsidies for electricity production, Act no. 377 of 2 June 1999; 1999.
[23] Christensen J. Commercialisation of biogas technologies—incentives and organisational aspects for future development. In: Proceedings for the kick-off for a future deployment of biogas technology. Biogas event 2000, 22–24 November 2000, Eskilstuna, Sweden 2000.
[24] Meyer NI. European schemes for promoting renewables in liberalised markets. Energy Policy 2003;31:665–76.
[25] Knoppen R. Denemarken schrapt alle DE-subsidies. Duurzame Energie 2002.
[26] Evald A, Jakobsen HH. Recent developments in Denmark. In: van Loo S, Hughes E, editors. Sheets from the joint meeting of IEA bioenergy task 32 and EPRI/biomass interest group industrially relevant, technical progress in developing biomass as a viable energy source, Feb. 19, 2003. IEA Bioenergy Task 21.
[27] Caddet. Energy from pre-sorted, organic household waste and manure, No. 93.: IEA/OECD; 1998.
[28] Escobar GJ, Heillilä MA. Biogas production in farms, through anaerobic digestion of cattle and pig manure. Case studies and research activities in Europe.: TEKES, OPET Finland; 1999.
[29] Nedergaard N, Ørtenblad H. Integration of biogas in municipal energy planning and supply. In: Holm-Nilesen JB, editor. The future of biogas in Europe. Risskov: BioPress; 1997.
[30] Centre of Biomass Technology. Danish Bioenergy Solutions: reliable and efficient.: Danish Energy Agency; 2000.
[31] Fisher T, Krieg A. Farm-scale biogas plants. Goettingen: Krieg & Fisher Ingenieure GmbH; 2000.
[32] Maegaard P. Biogas—A coming success.: Folkecenter for Renewable Energy; 2000.
[33] Hjort-Gregersen K. Danish farm scale biogas concepts—at the point of commercial breakthrough. Copenhagen: Danish Institute of Agricultural and Fisheries Economics; 1998.
[34] Köberle E. Development of medium scale biogas plants in Denmark. In: Proceedings, vol. 2 from the renewable energy and local production, September 18–23; 1988
[35] Wellinger A. Farm scale biogas concepts in Europe. In: Holm-Nielsen JB, editor. The future of biogas in Europe. Risskov: Biopress; 1997.
[36] Elmose O. Gårdbiogas.: Danish Energy Agency; 2002.
[37] Elmose O. Gårdbiogas.: Danish Energy Agency; 1997.
[38] Boon A. Vertical coordination of interdependent innovations in the agri-food industry. Thesis. Copenhagen Business School; 2000.
[39] Hjort-Gregersen K. Økonomien i gårdbiogasanlæg. Copenhagen: Statens Jordbrugs- og Fiskeriøkonomiske Institut; 1999.
[40] Garud R, Karnøe P. Bricolage versus breakthrough: distributed and embedded agency in technological entrepreneurship. Research Policy 2003;32:277–300.
[41] Raven RPJM. Strategic niche management for biomass. Thesis. Eindhoven University of Technology; 2005.